$\bar{p}$ Note # 469

"State of the Art in Optical Fiber Links for use as
Stochastic Cooling Delay Liners"

Bill Kells

For the purpose of upgrading the Luminosity of the Tev I $\bar{p}$ source it has been proposed to develop notch filtered stochastic cooling systems with 4-8 GHz effective bandwidths. It is unlikely that the current superconducting line technology will have sufficient performance at these frequencies due to increased dialectic loss and higher mode dispersion.

Here I survey fiber optics as a successor technology for the filter delay lines. Recent advance in single mode fibers, modulated diode laser sources and photodiode detectors suggest that the technology exists for our purposes. However we would be pressing on the state of the art in some areas, thus raising the question of the technology, accessibility.

I Fibers.

The established analog link technology is with "fat" (multi mode) fibers of ϕ = 50 -100μm which operate at 0.63μm or 0.84μm wavelengths. The demonstration device J. Simpson, et.al. built was of this type. [1] Dispersion is bad [relatively!] with this technology. First, intrinsic index of refraction changes as a function of frequency causing a "chromatic dispersion" ≃ 100ps/nm/km (that is, two tones different in wavelength by 1nm on a 1km cable have wave front transit time difference of 100ps). Secondly, the multimode nature of the cable allows a path length difference "model dispersion" ≃ 200ps/km. One can produce single mode fiber in this band to get the model dispersion to ≲ 2ps/km. However the effective bandwidth of the fiber due to the residual chromatic dispersion is:

$$\Delta\nu = \frac{1}{\pi}\,\nu_o\,[v_o\ (\text{dispersion})]^{-1/2} \qquad (1)$$

$$\simeq 6\ \text{GHz} \qquad (\text{for 325m length; 850nm band})$$

Where v_0 = fiber group velocity; and dispersion is $\Delta t/\Delta\lambda$ @ ν_0 for the given fiber length. Thus this technology is marginal for our application.

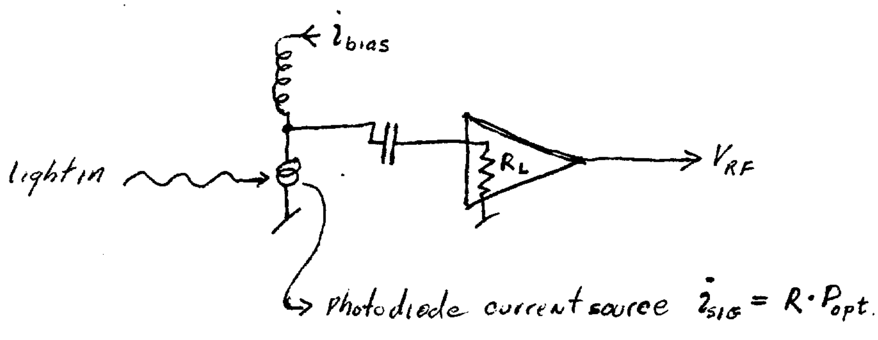
Chromatic dispersion can be dramatically improved by operating at wavelengths longer than 1.25μm (natural silica has a dispersion null at 1.27μm!). Cable is produced with ≲ 2ps/nm/km in this band (> 40Ghz bandwidth). Although there are several other advantages to these longer wave lengths (grater mode spacing, less damage to optical components, switches, etc.) much less hardware is readly available soutside of advanced development labs [2]). It is interesting to note that the single biggest advantage to ≥ 1.3μm is that attenuation, of critical interest in "long haul" communications, is way down too. But by current fiber standards, our cable lengths (325 meters) are short.

The present leading edge of research (No commercial devices) involves fiber in the ~ 1.6 μm band. This has been engineered to have both a dispersion and attenuation minimum. Thus it is of no particular interest for our current needs, since fiber in the 1.3μm band can achive ~ 0.6db/km loss. Practically, the great disadvantage of single mode fiber is making splices and connections with it. It is ether fused (best: ≲ 0.1db loss) or terminated with a jigging termination (≳ 0.2db & not 100% stable). Both methods of "pigtailing" require special equipment and expertise.

II Receivers.

The solid state photo-diode is the only reasonable choice here. Photodiodes (GaAlAs or silicon) developed for 0.53 or 0.84 μm have attained remarkable performance. Quantum efficiency of 70% is commercially available, as well as intrinsic device/package Bandwidths exceeding 20GHz. Noise is described as NEP (Noise equivalent Power) which has the somewhat odd units of Watts/$\sqrt{\text{Hz}}$. NEP means the CW incident laser power which produces a detector output signal just equal to its "dark" noise output power in a 1Hz Bandwidth. Since photo diodes produce current in proportion to incident light power, total threshold light power is only proportional to $\sqrt{\text{detector bandwidth}}$. High performance, fast (50Ω) devices have NEP < 2×10^{-14} watt/$\sqrt{\text{Hz}}$. Devices at 1.3μm are almost as good, being perhaps a factor of 2 worse in both NEP and quantum efficiency.

For our use the net noise floor of the detector system (photodiode plus preamp) can crucially constrain dynamic range. The "detector" model is:



Assume that R_{load} has an "effective" temperature T_R, whose Johnson noise determines the detector quiescent noise level (typical situation). Now we can compare broadband noise from various sources, referenced to preamp input, and for 1mw of laser power incident on the diode (typical):

Table I

$$P_{amp} = 4kT_RB \quad = \quad 6x10^{-12}W$$

$$P_{photon\ statistics} = (2e)ZB(\frac{1}{\sqrt{2}} R\cdot P_{opt}) = 2.7x19^{-11}W$$

$$P_{diode}\ (NEP) = \frac{1}{2}(R\cdot NEP)^2\ BZ = 10^{-17}\ W$$

$$P_{sig} = \frac{1}{2}(R\cdot OMD\cdot P_{opt})^2 Z = 0.2x10^{-5}W$$

where I use B = 4GHz; R (responsivity) = 0.45; Z=50Ω; OMD=50%; NEP=2X10^{-14} W/ Hz; and T_R = 100^{O}K. Notice that (2e) enters P_γ since a photon creates a hole as well as an electron. We are interested in $(P_\gamma + P_d + P_a)/P_{sig} \simeq 1.5x10^{-5}$. Actually the net dynamic range will be set by properties of the laser transmitter, such as IM distortion, cavity and model noise, as I discuss later. The conclusion is that for sufficiently high transmitted optical power, $P_\gamma/P_{sig} \propto P_{opt}^{-1}$ dominates, although attention does have to be paid to preamp quality.

III transmitters

The laser light source and its modulator are the most complex and performance constraining elements. Two approaches are being pursued by industry. The first consists of a CW laser whose output is modulated by a fiber ϕ scale electro-optical device. Since this approach clearly divorces many of the performance demands on the laser it has the most promise for Hi-Fi and large bandwidth. For instance super stable lasers (eg. YAG, as contrasted to semiconductors which are, because of size, inherently less stable, broader bandwidth & less powerful) can realize the P_γ limit on noise of table I. Unfortunately electro-optic modulators are a relatively new, less available, trickier to work with technology.

The simplest transmitter consists of AM modulation of the laser diode's current. Since the laser threshold is a super nonlinear function of this "pump" current, such a device is the obvious choice for standard high bandwidth (i.e. fast turn on/off time) to decouple the laser from the fiber. This greatly relieves the quality necessary for pigtail splices (a tricky business at best!) since minute reflections from such joints can cause degenorative noise in the laser, dominating RIN. Of course concatenating fiber-optical devices necessitates more of these splices. Needless to say the modulators, working on true wave interference principles, require single mode fiber technology.

The impressive state of the art may be appreciated by Fig 6 which gives a graphic feel for the technology as well. The main drawback from such devices is that their "on" attenuation is high; and their RF power consumption (for full off state) is also high. First this limits the P_{opt} input so that damage will not result. Second, the optical shot noise P_{γ} can begin to limit dynamic range. One must keep in mind that the main interest in such devices is for digital communications switching, where high "extinction ratios" are not required. The device of Fig 6 achieves < 15db extinction ratio for 120 mw rms microwave modulation while passing ~ 100μw of light ("on").[8] These are not circumstances where low distortion performance would be expected. I have not found any IM data in the literature.

Fig 7 shows the sole commercial product available in this technology. It is of the same Mach-Zehnder design described in Fig 6, having the inherent extinction ratio versus distortion problem. More recently, evanescent mode type devices have been developed[9] which work simply by making a light guide channel go into mode cutoff by RF modulating the refractive index. Such devices promise much greater efficiency (for a given extinction ratio) and so presumably will have lower distortion.

Several companies are on the verge of commercial products in our regime of interest. In particular a useful liaison with the nearby (Lisle!) fiber optics division of Amphenol is possible. They produce devices, but so far on a limited custom order basis. They are quite eager to pursue development projects. A particularly interesting possibility was raised in discussions with them; to make an "entirely light" correlator. More practically they can easily supply the technology to get us going on such expertise issues as [single mode] fiber splicing. A serious effort into the outboard modulator approach would probably, at this time, require contracting such outside expertise.

TABLE II

Wideband Laser Diode Transmitter specs. (ortel TLW-600s)

CHARACTERISTIC	VALUE - (Units)	
Supply voltage	+15	volts
Current consumption[6]	<120	ma.
P_{opt} Bias*	0.7	mw
P_{opt} max	1.0	mw
Operating temp	0-50	°C
Lasing wavelength	~1300	nm
Expected lifetime	$>10^5$	hr
Optical output (PIGTAIL) Φ	9	μm
RF Input (A.C. Coupled, SMA Connect)	50	ohm
Bandwidth (± 2.0db)	$<10^4$ $>6\times10^9$	Hz Hz
$P_{mod,max}$	13	dbm**
Modulation efficiency	0.5	mW_{opt}/V_{RF}
RIN (@ <2 GHz)	-135	db/Hz
3^D order IM intercept	+28 +23	dbm (2GHz) dbm (6GHz)

* Other ratings are for operation at this P_{opt}.

** Represents ≃ 40% OMD.

Relative Intensity noise (RIN) is the crucial system noise spec. (for systems where, as we saw above, the receiver noise is negligible), but can be a deceptive quantity. It must always be kept in mind that RIN only describes the intrinsic "noisiness" of a quicscently biased (i.e. lasing but unmodulated) laser. True system S/N will depend on other factors having to do with modulation level. Exactly:

$$\text{RIN} = 20 \log \left(\frac{\text{RMS A.C. Component of laser power output/Hz}}{\text{Average } P_{opt} \text{ laser output}} \right) \qquad (2)$$

Since the A.C. noise is always measured via a Power-current converting photo diode, the "20" means that RIN is related to noise power (1 Hz Bw) measured in a [noiseless] photodiode receiver (á lá table I). To determine a true, detected S/N power we must define S by specifying how P_{opt} is modulated. If the optical modulation depth ("OMD" -see Figure 3) is 100% (sine wave carrier), the resultant detected A.C. signal component has 1/2 as much power as the unmodulated [D.C] laser induced photodiode signal. Thus:

$$\text{SNR (db)} = -\text{RIN}-3\text{db} \qquad (100\% \text{ OMD } \underline{\text{only}}!) \qquad (3)$$

Actual RIN considerably exceeds the photon statistics limit (varying as P_{opt}^{-1}) and is found to vary $\propto P_{opt}^{-3}$. Infact RIN is also a function of frequency; the complex dependence of which is illustrated in Fig 4. Typically quoted RIN specs (e.g. Table II) are for worst case frequency but optimum P_{opt} conditions. Notice (Fig 5) that the RIN $\sim P_{opt}^{-3}$ dependence is deceiving since a given diode has absolute maximum power handling limits which are a <u>blend</u> of P_{opt} <u>and</u> P_{mod}. Thus running at $P_{opt,max}$ precludes any P_{mod} (i.e. OMD $\simeq$ o) so that SNR $\rightarrow$ o.

The true reality is best illustrated by an example (i.e. table II), which represents the laser biased on at an average output = 70% of its [P_{mod}=o] absolute maximum. Given this operating point, $P_{mod,max}$ = 13dbm which (using the modulation efficiency spec.) implies OMD=34%. This implies a detected SNR = +135 db - 3db - 20log 0.34 ≤ 123db/Hz. For our 4-8 GHz system, this gives a worst frequency point signal power density to noise denity ("dynamic range") = 27db (which neglects schottky band power density peaking!)

Operating the laser at high P_{opt} also increases the bandwidth of the device (Fig 4) although slowly: BW ~ $P_{opt}^{1/2}$. Fortunately at these high bias levels (70-80% of $P_{opt,max}$) 3^d order IM distortion is also acceptable. The intercept point quoted in table II corresponds to an IM noise floor -30db below signal (again, for <u>flat</u> schottky noise) at the worst frequency point (≥ 6 Ghz). The IM intercept is strongly frequency dependent, [6] so that most of the band has much lower IM noise floor. Notice that this effective dynamic range is considerably better than what Simpson's system achieved.[1]

The above discussion is based on rather strict interpretation of ORTEL literature. Conversations directly with them indicate that reality is more optimistic. Specifically, current production laser diodes will take up to ~ 50% OMD @ full $P_{opt,max}$, thereby improving the worst frequency SNR to > 30db. Second, much of the RIN is concentrated in spectral spikes which probably less effect our application (could filter). Most encouraging is that new technologies which make >10GHz bandwidth lasers available at 840nm will soon be available @ 1300nm.[7] Even now one can select individual devices (or wafer batches) which cut off at ≥ 75 GHz.

IV ELECTRO-OPTIC MODULATION

RIN dominated performance can be overcome by "outboard" modulation of an ultra stable laser. Since the laser is not modulated at high frequency it can be much larger & more powerfull. This reduces P_γ but also allows enough attenuation buffering digital fiber communications. Surprisingly it has been discovered [3] that such modulation does not excessively distort analogue signals, if the laser is biased on at a CW level well above lasing threshold.

A good deal of military emphasis has been placed on development of Hi-Fi, "secure", microwave, analogue data links.[4] Therefore some devices are commercially available. ORTEL [corp.] markets the most advance products. TABLE II illustrates a [commercial] state of the art device @ 1300nm. Inorder to appreciate these specs a careful interpretation is necessary.

First consider optical bandwidth/stability. At 1300nm it is very difficult to maintain lasing in one cavity mode [Fig 1]. Even th ough each mode has a very narrow width, we need to consider the mode <u>envelope</u> width, $\simeq$ 4nm. With fiber residual dispersion of $\leq$ 2 ps/nm/km; effective bandwidths > 20GHz are still possible. Note that Fig 1 is a <u>time averaged</u> spectral density. Actually the Laser tends to lase ~ 100% in a given cavity mode at any instant. It turns out that the technology to produce <u>single cavity</u> mode diode lasers at 840nm has been perfected, but we fortunately don't need this feature. The special envelope peak has a temperature sensitivity of ~ 0.3 nm/°C, so is quite controlable.[5]

By laser "transmitter" is meant a package which contains a gain servo loop on the optical power output in addition to the laser diode itself (see Fig 2). This is necessary since the lasers are designed to maximize the $\Delta P_{opt}/\Delta V_{mod}$ slope. For our cyclic stochastic cooling needs, careful attention to the band width of this loop will be needed so that it neither degrades the schottky signal, nor "fights" the cyclical average power variations!

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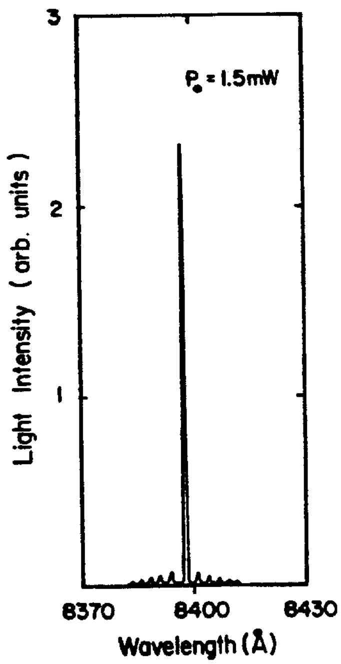


Fig. 1(a) Single mode spectrum

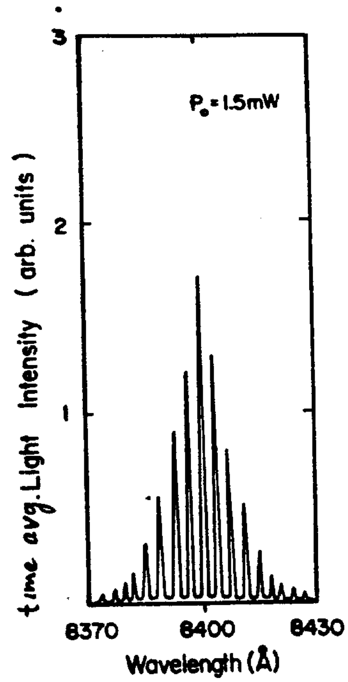
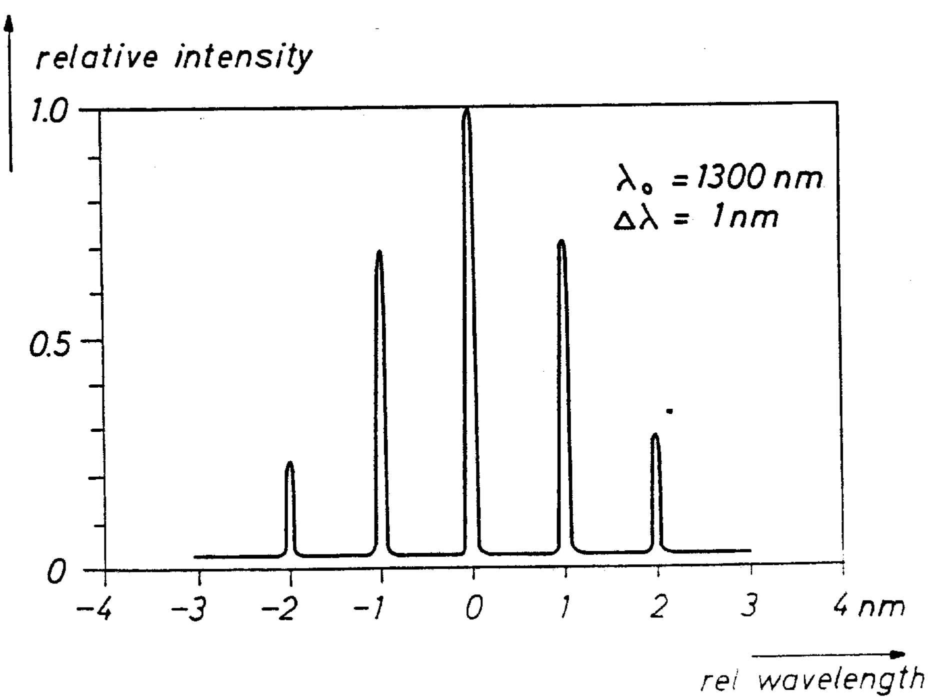


Fig. 1(b) Multi-mode spectrum

LASER SPECTRUM, 1300 nm



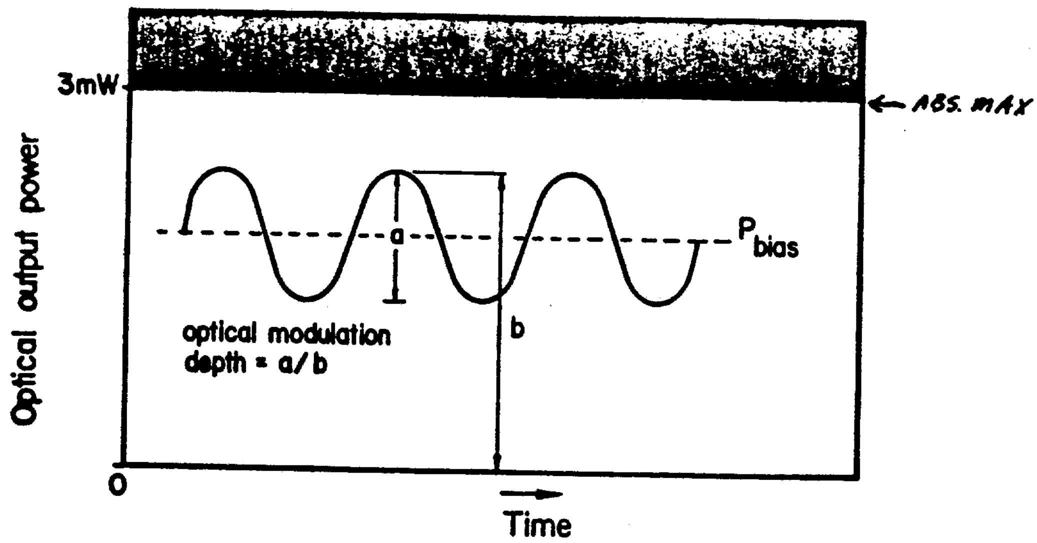


Fig. 3 **Optical modulation depth**

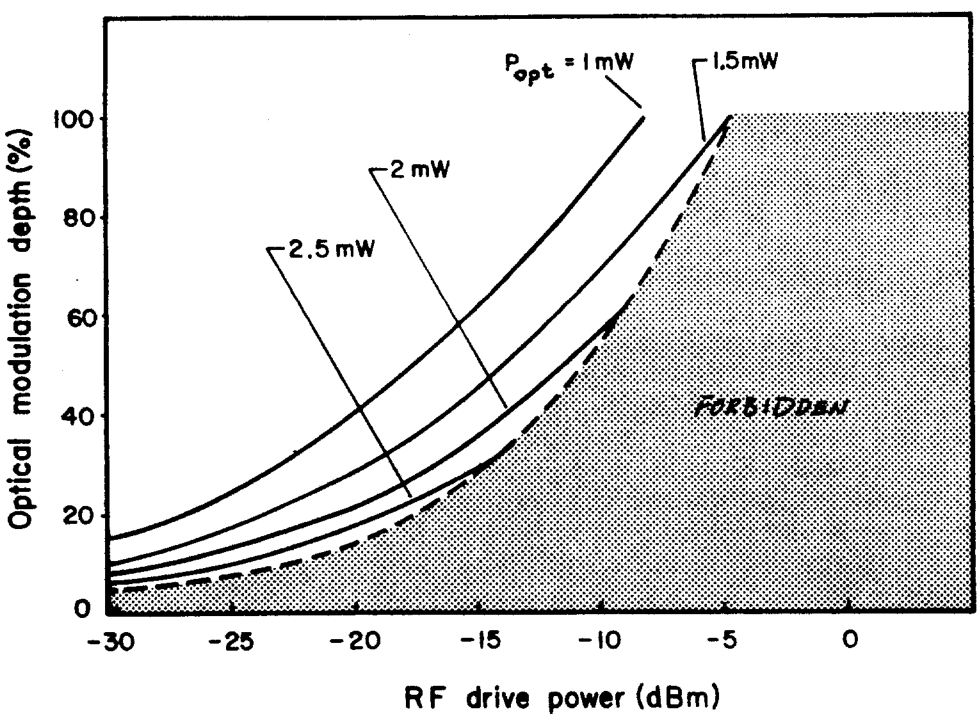


Fig. 5 **Modulation depth vs. RF drive**

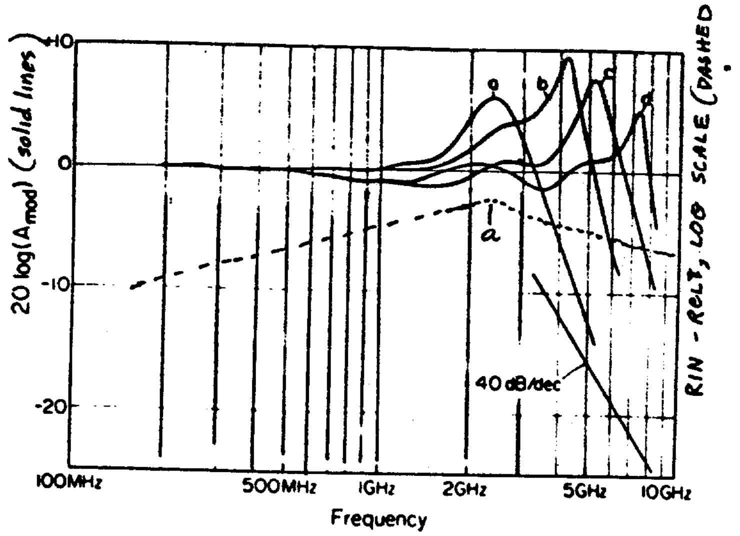


Fig. 4a Modulation characteristics of short cavity (120 μm) BH on SI laser at bias power levels of (a) 1 mW, (b) 2 mW, (c) 2.7 mW, and (d) 5 mW.

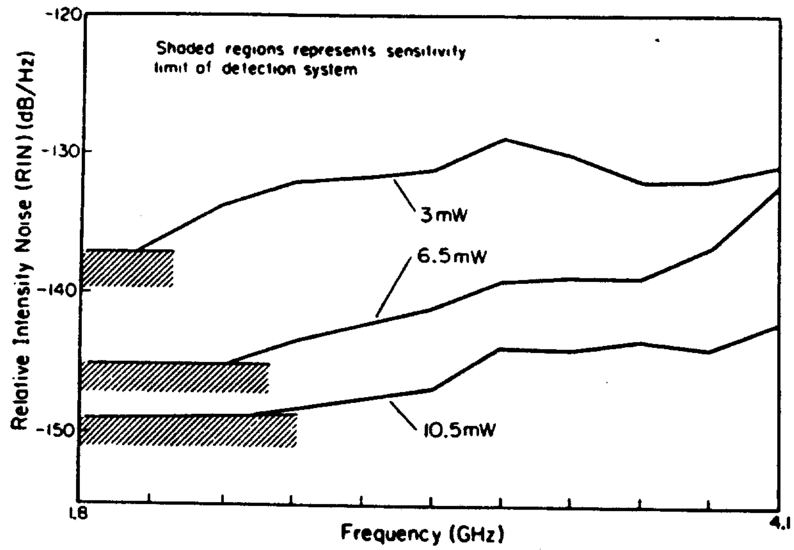


Fig. 4b The relative intensity noise (RIN) (different laser than Fig 4a)

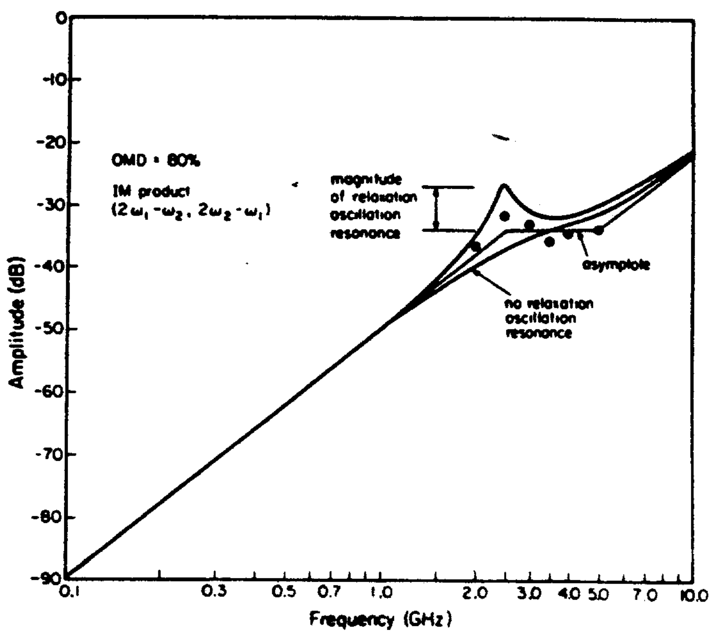


Fig. 4c Plots of third-order IM amplitudes as a function of signal frequency, at an OMI of 80 percent.

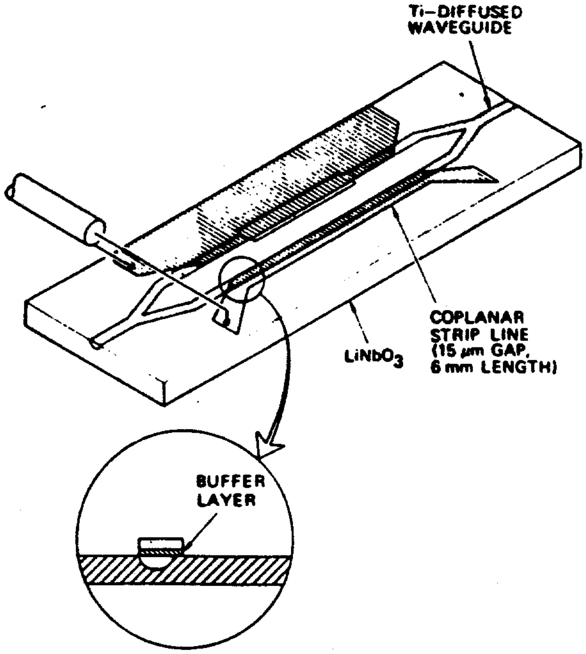


FIG. 6a Mach-Zehnder modulator with buffer layer (SiO_2 or ITO) separating the optical waveguides and the electrodes.

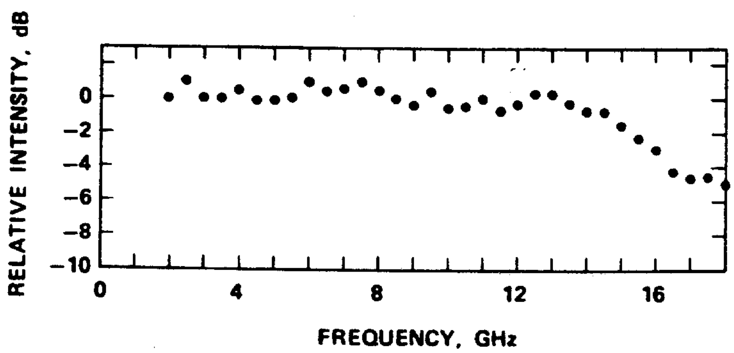


Figure 6b Modulator response as a function of frequency measured by a high-speed photodiode followed by an rf spectrum analyzer.

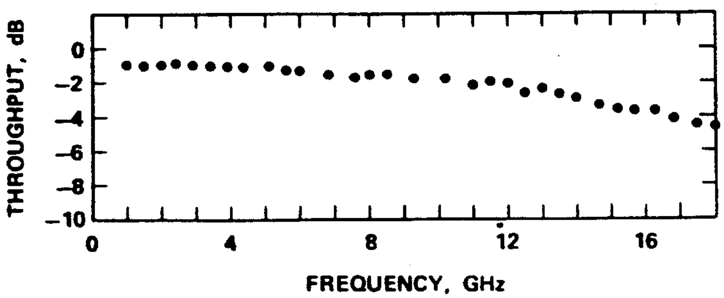
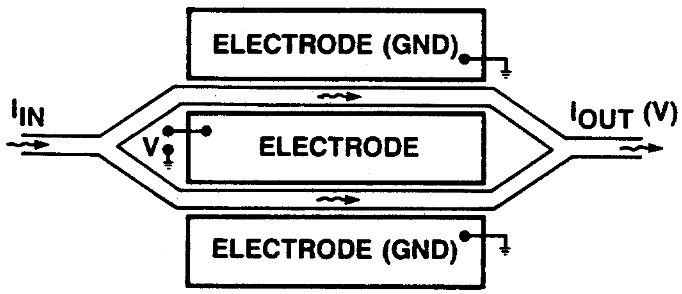


Figure 6c Microwave throughput as a function of frequency for the modulator. The rf loss is 1 dB at low frequency and decreases 3 dB at 17 GHz.



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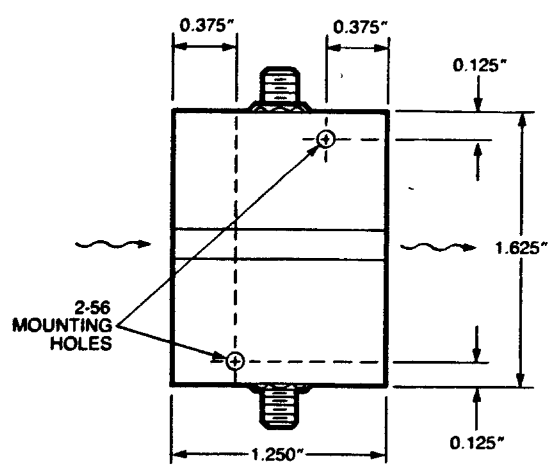
Package Dimensions	1.625″ × 1.250″ × .5″

NOTES:
1. Linear, small signal
2. Depending on wavelength and bandwidth.
3. Input and Output optical surfaces are polished for end-fire coupling.



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